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ABSTRACT

This report is part of a series from the Department of Energy on the use of solar energy in heating buildings. Described here is a new system for year around collection and storage of solar energy. This system has been operated at the University of Virginia for over a year. Composed of an underground hot water storage system and solar collection, the system was tested. Thermal performance results are presented. Analog and digital computer models were used to study the effect of various design modifications on collection and storage performance. (Author/MR)

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ANNUAL COLLECTION AND STORAGE OF SOLAR ENERGY FOR THE
HEATING OF BUILDINGS

Report No. 3

Semiannual Progress Report, August 1977-January 1978

By

J. Taylor Beard

F. A. Iachetta

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U.S. DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
EDUCATION

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January 1978

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University of Virginia
Charlottesville, Virginia



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Solar Energy

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I. ABSTRACT

A new system for year-round collection and storage of solar heated water for heating of buildings has been operated over the past year at the University of Virginia. The system is composed of an energy storage sub-system, which stores hot water in an underground pool, and of a solar collector sub-system which acts not only to collect solar energy throughout the year but also to limit the evaporative and convective heat losses from the storage system.

Results are presented to illustrate the transient heat transfer from the pool which occurs during the energy collection mode of operation. Thermal performance results are presented illustrating the efficiency of the solar collector under summer conditions (without a reflector) and winter conditions (with assistance from a vertical reflector). Results also show the transient behavior of energy storage in the water and in the earth which surrounds the storage pool.

An analog computer model and a digital computer model have been used to analyze the transient energy phenomena which occur within the earth surrounding the pool. Results of the models are confirmed by an exact mathematical solution and by experimental results.

Analog and digital models were used to determine the influence of various design modifications for improved collection and storage system performance.

The experimental system has been modified to provide for energy extraction through a heat exchanger, to simulate the heat input required

for a solar-assisted heat pump for a residential heating application.

Future research will include additional system operation in the collection and heat load mode, performance evaluation, and additional analytical modeling, particularly to identify the influence of additional design modifications on the system operation.

II. NOMENCLATURE

η	= collector thermal efficiency
ρ	= density
c_p	= specific heat
F_{RUL}	= slope of collector performance curve (heat removal $\times$ loss coefficient)
k	= thermal conductivity
$\dot{Q}$	= heat loss
$\dot{Q}_o$	= heat loss with earth berm perfectly insulated
R_e	= radius to outer isothermal boundary
T_a	= ambient temp.
T_e	= earth temp. at R_e
T_{in}	= collector inlet water temp.
T_{c1}	= centerline earth temp. at pool/earth interface
T_{c2}	= centerline earth temp. at 1 ft. below pool
T_{c3}	= centerline earth temp. at 2 ft. below pool
T_{c4}	= centerline earth temp. at 3 ft. below pool
T_p	= average pool temp.
T_{p1}	= centerline pool temp. at top surface
T_{p6}	= centerline pool temp. at 5 ft. depth
T_{p11}	= centerline pool temp. at 10 ft. depth.
T_{w1}	= earth temp. on 45° pool/earth interface
T_{w3}	= earth temp. 3 ft. from 45° pool/earth interface
T_{41}	= earth temp., 4 ft. from pool edge, 1 ft. down
T_{42}	= earth temp., 4 ft. from pool edge, 2 ft. down
T_{44}	= earth temp., 4 ft. from pool edge, 4 ft. down
T_{46}	= earth temp., 4 ft. from pool edge, 6 ft. down

III. NARRATIVE

A. Research Objectives

The research objectives include the design, construction, testing and evaluation of a new system for year-round collection and storage of solar energy for the heating of buildings.

The design of the system includes a 103 m^3 (27,400 gal) water storage pool which resembles a swimming pool. The collector sub-system is that of a 53.5 m^2 (576 ft^2) near horizontal open water-channel solar collector having two glazings. The solar collector acts not only to collect solar energy but also to reduce losses from the energy storage pool. Design modifications for improved structural and thermal performance are an important part of the research objectives.

The testing and evaluation program has included the use of standard instrumentation and measuring techniques as well as analytical simulation to determine performance under varying ambient and design conditions. The evaluation also will include structural, operational and economic considerations.

B. Summary of the Progress

A new system for year-round collection and storage of solar heated water for the heating of buildings has been constructed and is being evaluated at the University of Virginia.

In the first year the research included developing improved structural and system design with construction, system operation in the collection mode, testing and evaluation.

Construction of a revised pool design with 103 m^3 (27,400 gallons) of water capacity was completed in November 1976. The solar collector, shown in figure 1, became operational in February 1977.

Various modifications have been made such as the installation of a vertical reflector along the north edge of the pool shown in figure 2, improved glazing attachment, and improved instrumentation for monitoring energy collection and energy loss through the earth berm.

During the fall of 1977 it became obvious that energy losses were becoming significantly greater than energy collection. A study of possible ways to improve the insulation quality of the storage resulted in the conclusion that a full system shut down would be required in order to provide the proper improvement to the insulation. This was judged to be appropriate for follow-on work after the system had been operated throughout the 1977-78 heating season. A decision was made to continue system operation in the heat collection mode with a modified plan for energy extraction. A heat exchanger was provided to simulate the heat input requirements for a solar assisted heat pump for a residential heating application. The system began operation in the heat load mode (with solar collection, when available, as before) in December 1977.

Results are presented of analog and digital computer simulations which illustrate the influence of design modifications on system performance in the collection mode of operation.

Future research will include simulations of other design modifications (such as larger size systems with independent collector arrays) and experimental analysis of system operation in the heat load mode.

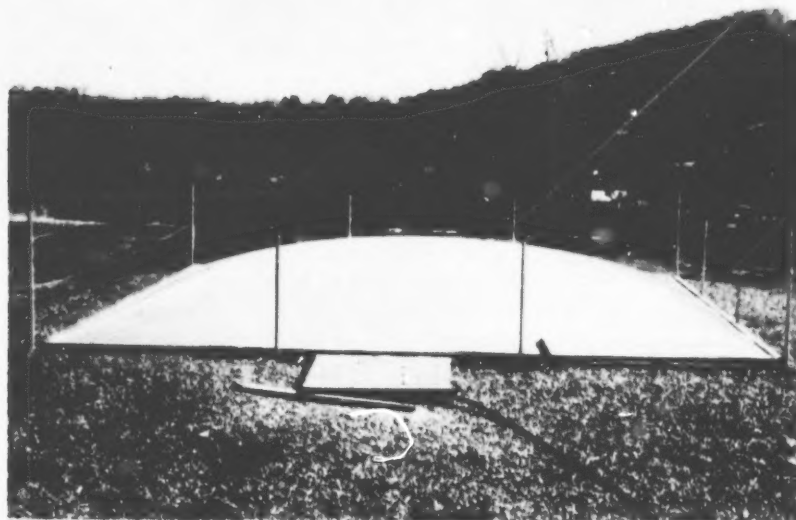


Figure 1, Annual Collector/Storage System, February 1977

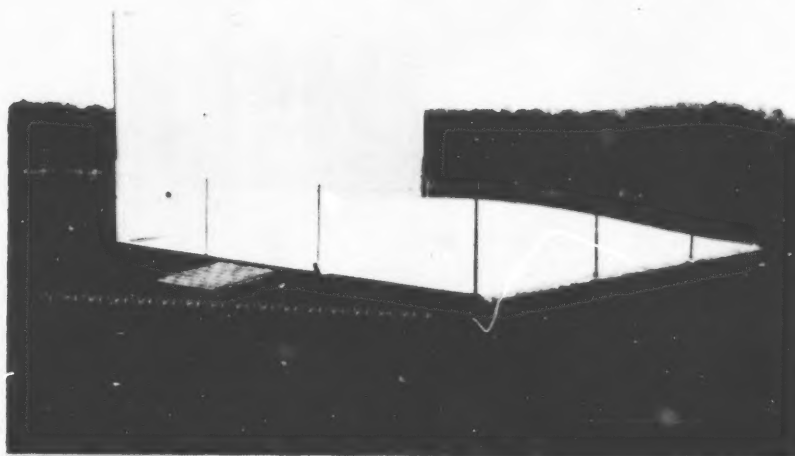


Figure 2, Annual Collection/Storage System, March 1977

C. Report of the Progress: System Description

In May of 1976, the University of Virginia began its research program to evaluate a new system for the year-round collection and storage of solar-heated water which could be used for the heating of a building. The system includes a 53.5 m^2 (576 ft.^2) solar collector on the top of a 103 m^3 (27,400 gal) energy storage pool which resembles a swimming pool. Included in the collector are the near-horizontal absorber surfaces, the inner glazing and the outer glazing shown in Figure 3 and the inlet manifolds shown as a top view in Figure 4. The location of the solar collector on the top of the storage pool restricts the convective and evaporative heat transfer relative to that of traditional solar pond systems [1].

As illustrated in Figure 3, the energy storage pool is designed with the sloping earth surfaces at 45° . This design was selected because of the stability of such surfaces without a requirement for structural reinforcement. A traditional swimming pool having vertical walls with reinforced concrete structural support could be used in this system; however, the cost of the reinforced wall structure would be considerable and was judged to be unnecessary.

The pool design includes a factory manufactured 20-mil polyvinyl-chloride swimming pool liner. All the seams were heat sealed at the factory to assure their integrity. In addition, special care was taken to ensure that this liner would not be punctured. The earth surfaces were smoothed as much as possible and a duPont Company "Tyvar" (spun-bonded polypropylene) subliner was installed on the earth surfaces to

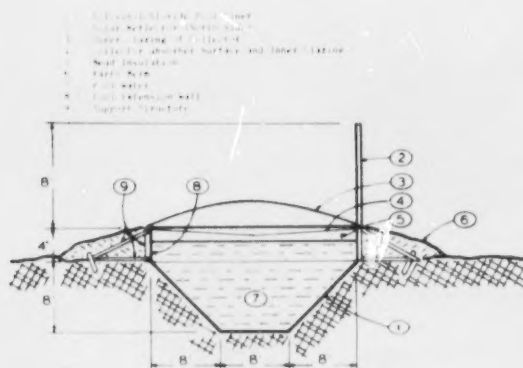


Figure 3. Solar System Design

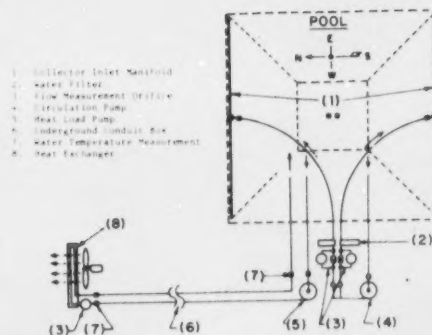


Figure 4. System for Monitoring and Delivering Water

1. Outer Glazing
2. Inner Glazing
3. Collector Inlet Manifold
4. Corrugated Aluminum Collector Plates
5. Collector Mounting Bracket
6. Collector Support Cable/Rod
7. PVC Pool Liner
8. Plywood
9. Rim Strip
10. Batten Strip
11. Spline
12. Pool Liner Anchor Strip
13. Batten Support Strip

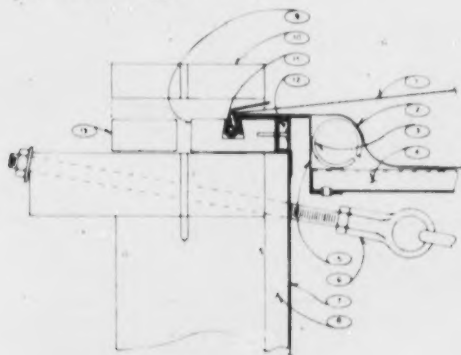


Figure 5. Collector Details

1. Outer Glazing
2. Inner Glazing
3. Corrugated Aluminum Collector Plate
4. Support Cable
5. Support Structure
6. Styrofoam Beads Floating on Water Surface
7. Collector Water Outlet

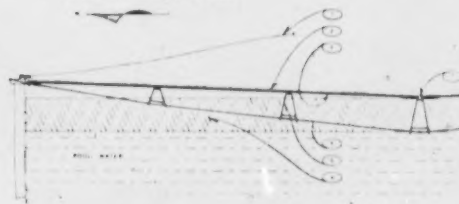


Figure 6. Collector Support Detail

prevent migration of sharp stones, etc., from penetrating the liner.

The solar collector selected for the annual collection/storage system is that of a near-horizontal open water-channel solar collector having two glazings as indicated in Figures 5 and 6. The glazing materials are separated by air pressure from a small fan (47 watts) with the inner glazing lying on top of the corrugated metal collector plate. Water flows from the north and the south perimeters of the collector system down the valleys of the corrugations to the center of the pool where it exits and flows through a layer of styrofoam beads floating on top of the water surface.

The glazing material which has been selected is that of a 6-mil thick greenhouse film sold as Monsanto 602. This is a flexible polyethylene "copolymer" greenhouse covering which has a transmittance of 88%. It has been widely used throughout the United States and is available in an adequate size to cover the pool in a continuous sheet. Although it is very inexpensive for a glazing material (\$0.28 per square meter) the outer glazing was found to sustain a 8% reduction in transmittance over a five (5) month period of use. The outer glazing was replaced with new Monsanto 602 in July 1977.

D. Report of the Progress: Collection Mode of Operation

The collection and storage system began operation in late February 1977. When adequate solar energy is available, the collection system is turned on by a controller. The hot water from the solar collector flows through the floating beads at the centerline of the pool and into the top of the hot water storage.

One should note that the collectors are near-horizontal which is not the desired orientation, particularly for winter solar energy collection. A vertical reflector has been constructed along the north edge of the collector to increase the energy capture, particularly during the winter months.

Figure 7 displays the thermal performance of the collector as a plot of $(T_{in} - T_a)/I$. One should note that the reflector was not up when the summer performance data were obtained. Also, the winter performance calculations did not provide for the energy intercepted by the reflector to be included in the denominator of the efficiency (output : input) calculation. Consequently the winter performance curve gives a false impression of a reduced value of F_{RUL} (slope). It is important to note that the reflector is very important to winter solar energy collection for typical values of $(T_{in} - T_a)/I$ around $0.08 [^{\circ}\text{Cm}^2/\text{w}]$.

Figure 8 presents the temperatures observed for the seasonal solar energy storage pool. One notes that the pool and earth temperatures rose steadily until the months of August and September, but then dropped off rapidly. The obvious reason for this change is that the variation in incident solar energy and ambient temperature with season and the fact that the storage pool does not have adequate size or insulation to reduce the relative losses. This experimental observation is consistent with the experience the similar sized pool installation at Ohio Agricultural Research and Development Center [2].

One should note that no programmed energy extraction from storage has occurred for the time period of the data presented. An energy

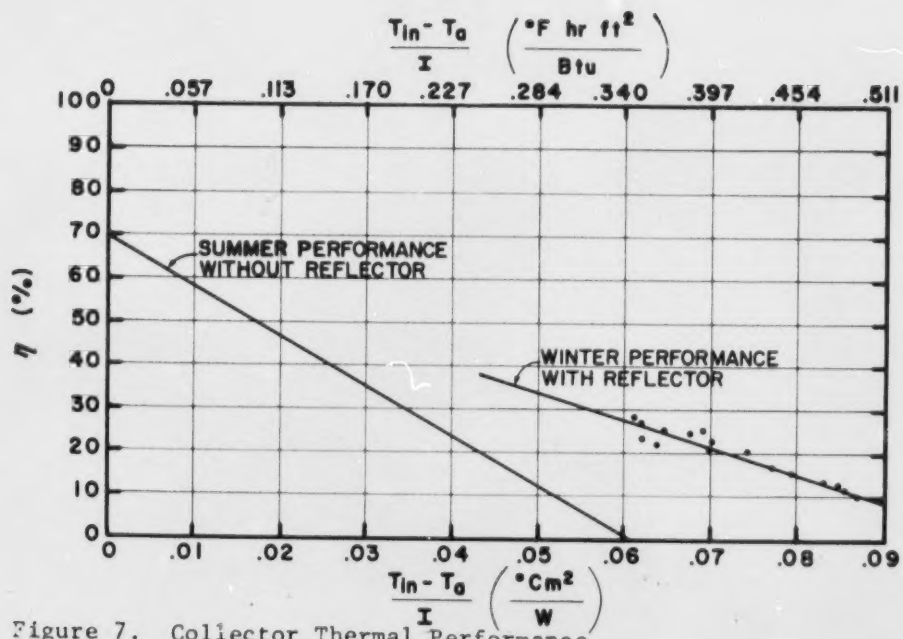


Figure 7. Collector Thermal Performance

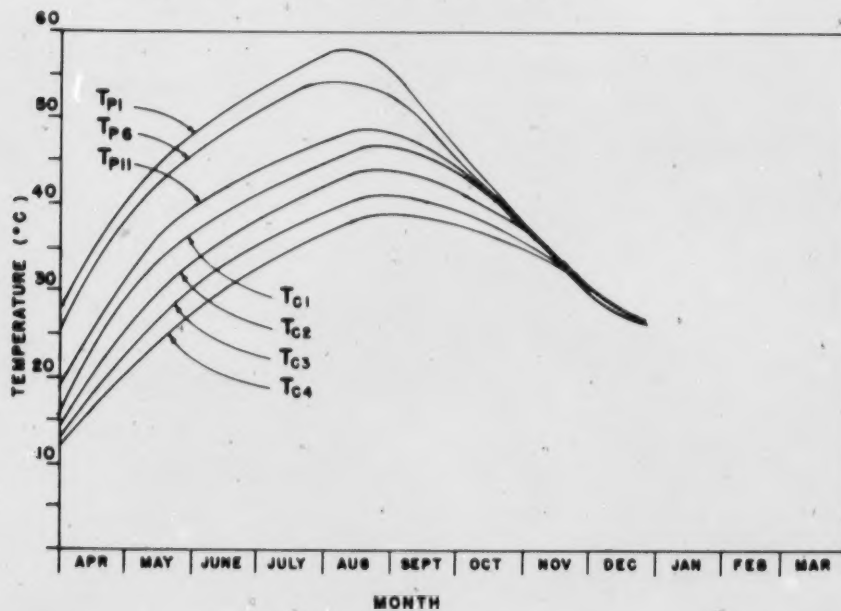


Figure 8. Seasonal Temperatures of Storage System

extraction program began operation in December 1977 with energy (hot water) being delivered to a heat exchanger in a proper amount to simulate the requirements of a heat pump for a residential application. The heat load mode of operation is described in a later section.

E. Report of the Progress: Energy Loss Analysis

Energy losses from such solar pools occur by various heat transfer mechanisms and can be attributed to the heating up of the surrounding soil, conduction losses from the top surface directly to the atmosphere, and losses through the soil to the atmosphere. These losses depend on the size and the geometry of the pool, the energy input to the pool from the solar collector, the meteorological conditions and the physical properties of the system.

E-1. Analog Model Description

An electrical resistance-capacitance network has been set up to simulate the heat transfer processes from a hemispherical pool of water to the surrounding soil and through the soil to the ambient air. This network used a modified version of the Heat Exchange Transient Analog Computer developed by R. M. Hubbard [3]. In this analog the temperature is represented by a voltage, the rate of heat flow by current, and thermal resistances and capacities by electrical resistors and capacitors. By using appropriate scaling laws [4], a network can be set up to represent the thermal capacitance and heat transfer resistances for a particular pool geometry. The network can accept properly scaled time-dependent solar energy input and variable ambient and energy demand conditions. Selected parameters can be adjusted easily so as to simulate different design conditions.

For the initial simulation of the storage pool heat loss problem, we chose to consider heat transfer by conduction through soil of uniform and constant physical properties. A hemispherical pool of water was chosen. The soil surrounding the pool was divided into 24 elements as illustrated in figure 9, with nodal points (at the center of each element) interconnected by resistors representing thermal resistances between adjacent points. A vector volume approach [4] was used to determine the effective resistance as the area normal to heat flow changes with both radial and angular positions. The capacitance of each element is directly proportional to its volume. Since the hemispherical heat source has symmetry, only a slice of the surrounding earth need to be considered.

The boundary conditions were applied by connecting the adjacent nodes to appropriate resistors and to voltage sources representing the desired boundary temperatures.

The properties of soil used in the simulation were fixed with:

$$\rho = 1,500 \text{ kg/m}^3$$

$$c_p = 880 \text{ J/kgK}$$

$$k = 1.28 \text{ w/mK}$$

Scaling factors were determined largely by the size and number of resistance and capacitance elements available. The following relations were set between the important variables:

$$1 \text{ volt} = 1^\circ\text{C}$$

$$1 \text{ analog second} = 1 \text{ week real time}$$

$$1 \text{ microampere} = 3.84 \text{ kw hr/day heat rate}$$

To obtain the above scaling factors, resistors ranging from .26 to 18.6 megohms and capacitors from 0.226 to 440 microfarads were needed.

E-2 Digital Simulation Model

A digital computer simulation model has been developed with the following four components: (a) a one-dimensional finite difference model of the thermally stratified pool of water; (b) a three-dimensional finite difference model of the surrounding soil; (c) a solar collector model based on experimental thermal performance data; and (d) a simple model of the load.

As illustrated in figure 10, only one-eighth of the pool and surrounding soil are modeled because of symmetry (no heat flux across planes of symmetry: D, G, and H, shown in figure 10). The boundary condition at the top of the simulated pool is set by the condition of the solar collector. Boundary conditions at planes A and C originally allowed for convective heat transfer [5]; however, the temperatures of the surface nodes with the convective boundary conditions were found to be essentially equal to the ambient temperature. The distance from the pool to boundaries E and F were determined by trial running of the program. A distance of 6.1 m (20 feet) was found to be adequate. Moving these boundaries by approximately 1.2 m or 4 ft. had less than 1.5% effect on the heat loss from the pool.

E-3 Model Verification and Experimental Results

To validate the analog network, the steady state conduction was simulated through a spherical shell with a cavity at a higher temperature than the outer surface. These results are summarized in Table 1. It is interesting to note from Test 1 and 2 that having the constant ground temperature at a finite radial distance of 38.9m from the center of the pool rather than at infinity increases the pool heat loss rate by approximately 10%. The losses to the earth further out may be overestimated slightly but this effect would

TABLE 1

MODEL VALIDATION: STEADY STATE

Pool Temperature $T_p = 82^\circ\text{C}$ Earth Temperature $T_e = 10^\circ\text{C}$

Test	Model	Air/Ground Surface	Const. Temp. Earth at R_e , m	Pool Heat Losses kW-hr/day
1	Theory	Insulated	∞	64.8
2	Theory	Insulated	38.9	71.4
3	Analog	Insulated	38.9	72.6
4	Digital*	Insulated		73.2
5	Analog	$T_a = 21^\circ\text{C}$	38.9	124.6

NOTE: Digital model for truncated pyramid shape. Constant temperature earth at 6.1m from pool sides and bottom.

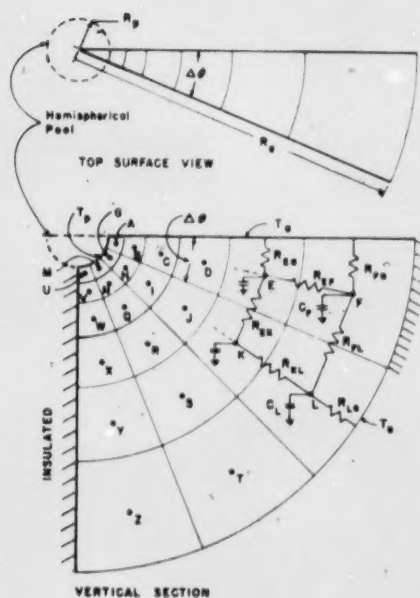


Figure 9. Analog Model Elements

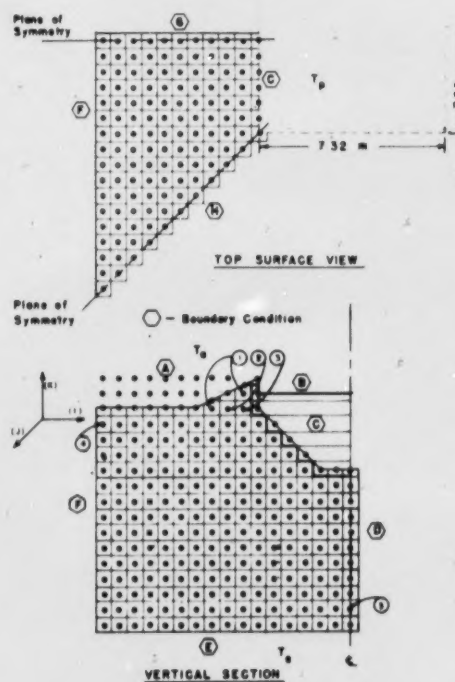


Figure 10. Digital Model Elements

be conservative in considering the performance of the storage pool. The agreement between Test 2 and 3 was excellent.

The digital model was also evaluated under the conditions listed in Table 1. Note that good agreement was obtained between the digital model and the analog model under the conditions where the analog model had a pool perimeter equal to that of the actual pool and the simulated model. This was based on Shelton's conclusion that the heat losses from a hemispherical pool are proportional to the perimeter (radius) rather than the heat transfer surface area (radius²) [6].

Steady state heat losses from the pool have been simulated over a range of pool, ground, and ambient temperatures. Shelton has analyzed heat losses from a similar hemispherical heat storage device [6]. However, Shelton's results were all based on no heat losses from the soil to the air through the soil-air interface. By considering this heat loss mechanism, the energy losses are considerably increased (approximately 70%) as shown by Test 6 in Table 1.

The limiting (steady state) heat loss results are summarized in figure 11. Note here that the simulated pool losses (which include losses to the ambient as well as to the constant temperature earth) appear to be approximately linear with the difference between the pool temperature and the air temperature. From figure 12 one can discern that the influence of pool temperature minus earth temperature is much less significant than pool temperature minus ambient temperature.

Results of experimental data for the annual collection and storage

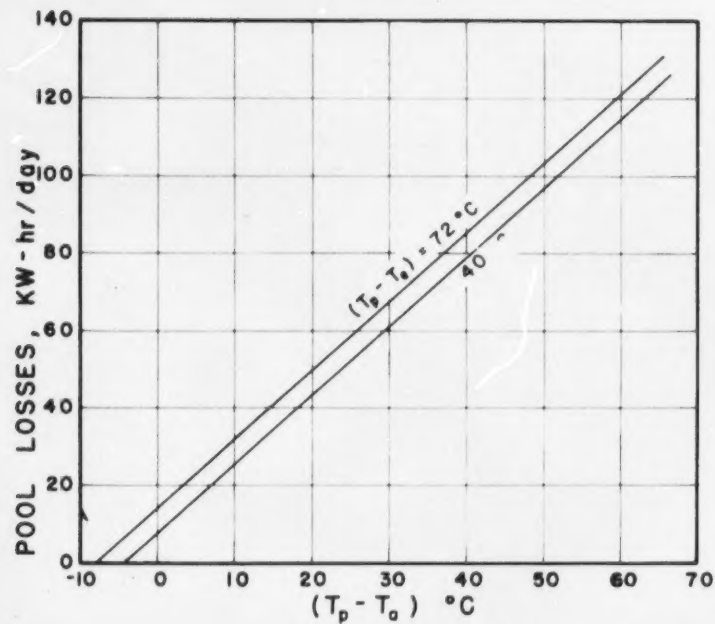


Figure 11. Steady State Energy Loss As Function of $(T_p - T_a)$

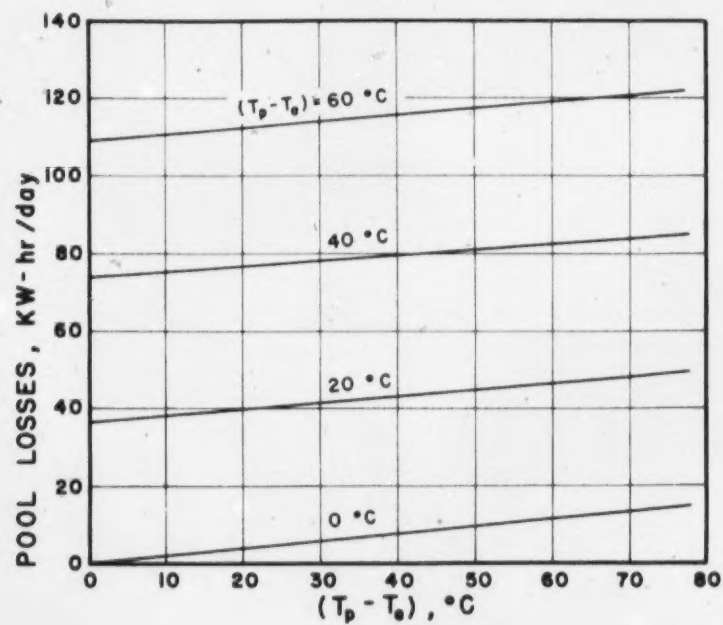


Figure 12. Steady State Energy Loss as Function of $(T_p - T_e)$

system operating in a collection mode were presented in figure 8. One notes that the water storage temperatures were shown to reach a maximum in August which would be an indication of excessive heat losses over energy collected from that time forward.

The digital computer simulation model was run using ambient conditions derived from a 1955 weather tape for Washington, D.C. Although it is clear that the particular weather conditions at the experimental site during 1977 are different from those used in the simulation, the following conclusions can be made.

Simulation shows, as illustrated in figure 13, that a cyclic pool temperature should be expected. The simulation indicates a peak temperature reached on approximately August 1 when the pool had been operating in the collection mode at least since early March. If the pool began operation in the collection mode on July 1, the expected peak temperature would occur approximately September 1 and if the pool began operation on October 1, the peak temperature would occur at approximately November 1. Note also that if the pool had been operating in the collection mode for at least six months, the influence of start up time would be negligible compared to the anticipated temperatures from continuous operation in the heat collection mode.

Pool stratification determined experimentally are in good agreement with the simulation model, as illustrated in figure 14.

Although simulation studies have not been done to consider the influence of diurnal variations of temperatures in the earth berm (adjacent to the pool), experimental measurements have been taken. Figure 15 illustrates the diurnal

variations of the ambient temperature and soil temperatures at various locations. One should note that these data were taken on a sunny day (October 7, 1977) followed by a cloudy day having a very light rain. Note also that the ambient temperature and the earth berm temperature to a depth of one foot have significant diurnal variation, but that the earth temperatures at locations below this appear to have near negligible diurnal variations.

F. Report of the Progress: Influence of Design Changes

On the basis of information presented in the previous section, one may conclude that the high heat losses from the present experimental system make it ineffective for operation as a device for annual storage of year-round collected solar energy for direct heating of buildings. Various design modifications, however, may change this conclusion.

The first design consideration would be that of modifying the system in order to provide for additional insulation. Table 2 summarizes the results of analog simulation studies of the influence of varying amounts of insulation placed at convenient locations within the earth berm. Note that one may conclude that a most important location for placing insulation would be along the interface between the pool structure and the earth berm. This is true because the earth berm in this particular design is relatively ineffective as an insulator, when one considers steady heat transfer over long periods of time.

The effect of insulating the soil/air interface along the earth berm is illustrated in figure 16. The heat loss rates are made non-dimensional 23

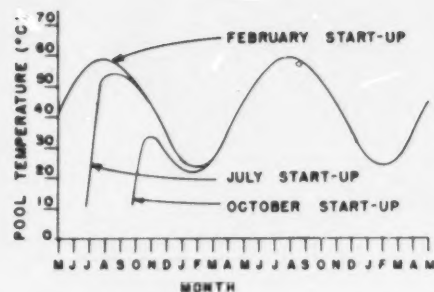


Figure 13. Simulated Seasonal Temperatures with Variable Start-Up

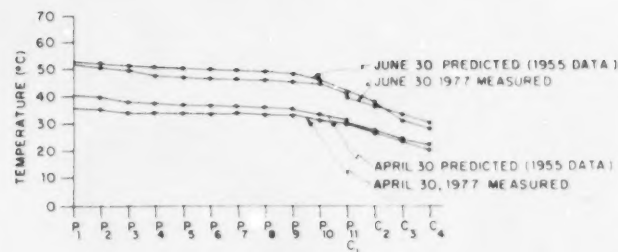


Figure 14. Pool Stratification

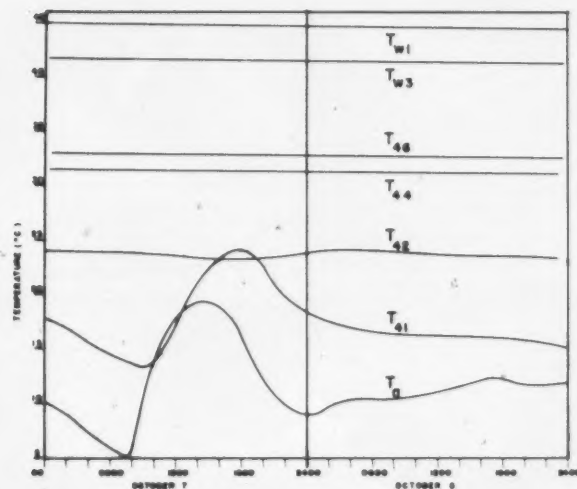


Figure 15. Diurnal Temperatures of Ambient Air and Soil at Selected Locations

TABLE 2

EFFECT OF INSULATION ON POOL HEAT LOSSES

Heat loss results in (kw-hr/day) from analog model with

Pool Temp. $T_p = 51^\circ\text{C}$

Ambient $T_a = 22^\circ\text{C}$

Earth $T_e = 10^\circ\text{C}$

Pool Side Insulation (b), m	Surface Insulation (a), m				
	None	0.025	0.15	0.31	"
None	62.5	56.6	49.3	47.6	45.0
0.025					41.6
0.15	19.3		15.0 ^(c)		16.7
0.31					15.0
"	16.1				11.5

Notes: (a) 1.75m wide "Styrofoam" insulation on earth/air surface around the pool (horizontal).

(b) 1.40m high (vertical from water surface) "Styrofoam" insulation between pool liner and earth.

(c) 4.34m wide horizontal insulation layer around the pool buried 1.5m below air/earth surface.

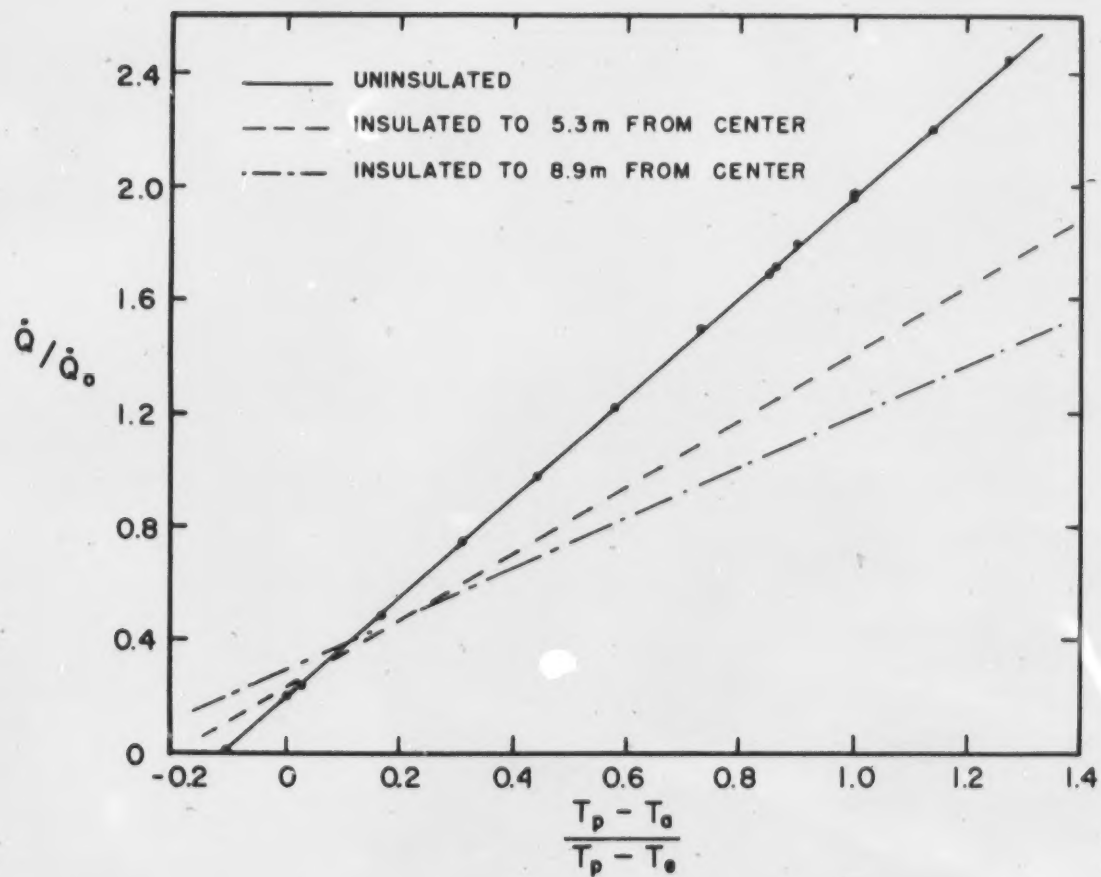


Figure 16. Heat Loss as Function of Soil/Air Insulation

through the use of $\dot{Q}_0$ which is the pool energy loss rate with the soil/air interface perfectly insulated. Note that the solid line in figure 16 would be the anticipated heat transfer from an uninsulated pool through the surrounding earth. This figure also shows the effect of insulating the soil/air interface close to the pool. The area between element "A" of the analog model (figure 9) and the ambient air is a ring with the inside radius of 3.57m (pool radius) and the outside radius of 5.32m. The effect of perfectly insulating this ring of the soil/air interface is shown by the dashed line. If the ring of insulation were extended to include an outer radius of 8.89m (insulating both elements "A" and "B") the heat transfer would be represented by the dot/dash line.

A second design consideration would be to improve the solar collector so as to deliver more energy to storage to offset the losses. One approach would be to improve the orientation of the collector, as near-horizontal collectors are poor collectors except during the summer. This would involve a redesign of the current system, so as to possibly provide for a structural roof over the storage pool, with the collectors mounted on the roof.

Another approach to improved collection would be to use an enclosed-fluid flat plate solar collector instead of the open water-channel collector currently used. Such a change would result in a smaller value of FR_{UL} (slope of the performance curve, Figure 7), and consequently higher collection during winter. This approach was investigated with the use of the digital computer model with the collection mode results illustrated in Figures 17, 18, 19 and 20.

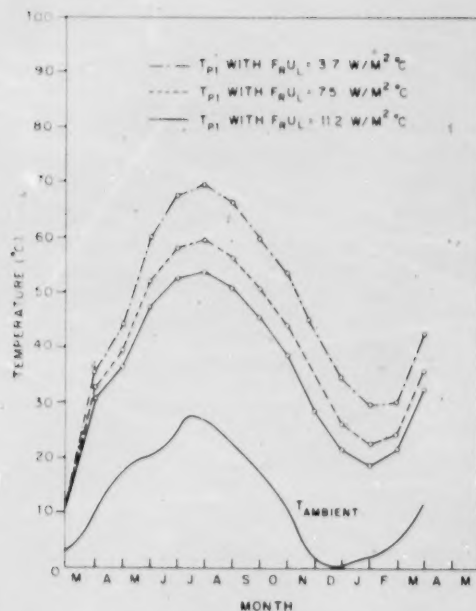


Figure 17. Predicted Storage Temp. for Systems with 3 Collectors

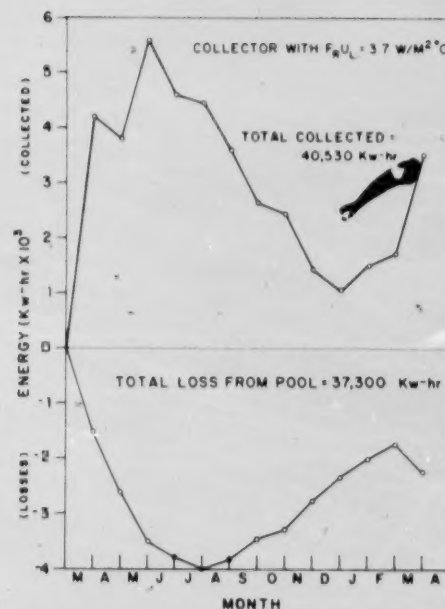


Figure 18. Collected and Lost Energy with $F_{RL} = 2.2 \text{ w/m}^2\text{°C}$

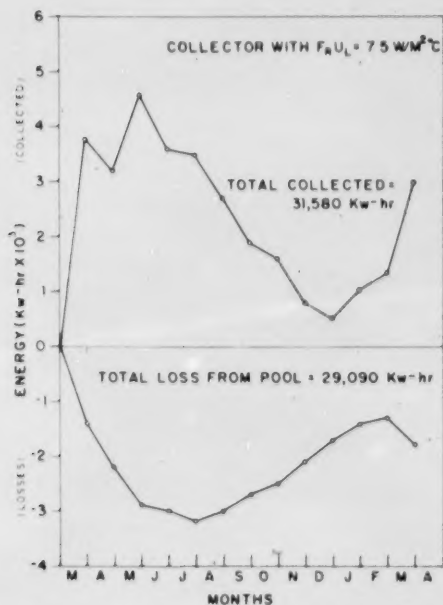


Figure 19. Collected and Lost Energy with $F_{RL} = 4.4 \text{ w/m}^2\text{°C}$

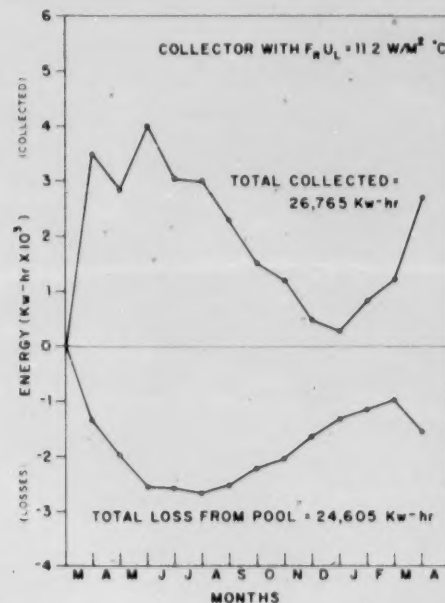


Figure 20. Collected and Lost Energy with $F_{RL} = 6.6 \text{ w/m}^2\text{°C}$

One other design approach would be to significantly increase the size of the collection and storage system. Various investigators have proposed much larger collection areas and storage volumes to gain the effect of relatively lower heat losses [7,8,9,10,11]. Typically heat losses increase with the perimeter of the storage, and collection increases with the area [6].

Various size, geometric, and design considerations will be studied in the next phase of this work. Included will be modeling of various design modifications with system operation in the collection and heating mode, considering both direct heating and solar assisted heat pump operations.

G. Report of the Progress: Heating Mode of Operation

In December 1977, the annual solar energy system was modified to provide for energy extraction through a heat exchanger. Heat extraction was designed to simulate the heat input to a solar assisted (liquid to air) heat pump used for heating a 140 m^2 (1500 ft^2) residence. The residence used in the model was assumed to be insulated to present standards and to have less than 15 percent glass area in the walls [12]. The heating load for such a structure is 12,650 Btu per degree day. The total annual heating load for this home would be 15,600 kw-h (53.2×10^6 Btu), based on an 11 year average of Charlottesville, Virginia weather data [13].

The heat pump used in the model was a commercially available water source heat pump [14]. The heat pump model has a COP of approximately 3.3 to 3.7, for water temperatures of 15 to 24°C (60 to 75°F). For inlet water at 15.5°C (60°F) and a flow rate of $1.14 \text{ m}^3/\text{hr}$ (5 gpm), the unit capacity is 7.6 kw (26,000 Btu/hr) with an energy absorbed from water of approximately

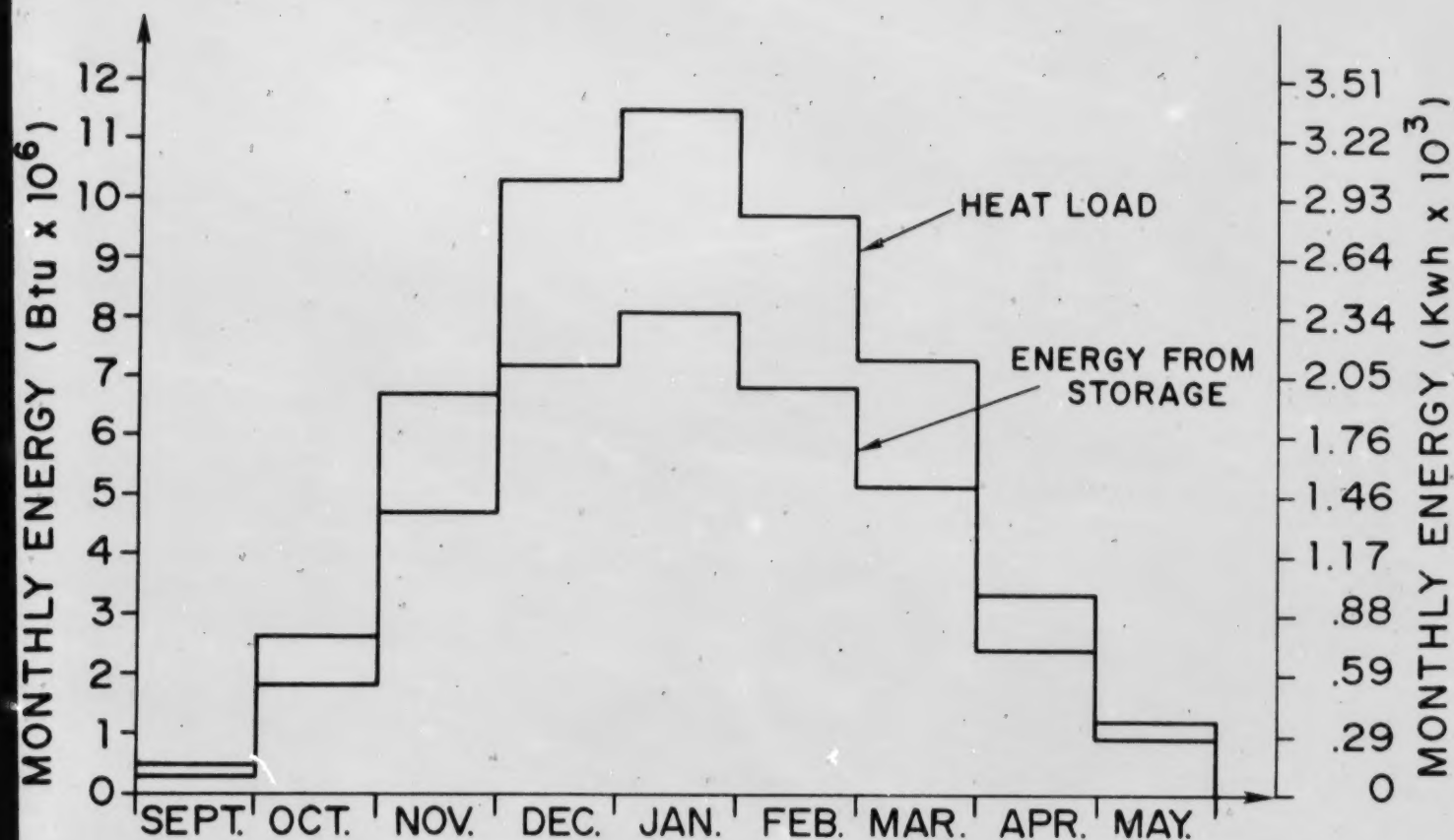


Figure 21. Monthly Energy for Heating with Solar Assisted Heat Pump

5.6 kw (19,000 Btu/hr) and a power input of 2.2 kw. For an inlet water at 23.9°C (75°F) the unit capacity is 8.8 kw with 6.2 kw from water and 2.6 kw from power input.

The average monthly total space heating demand and the requirements for energy input from solar heated water storage are illustrated in Figure 21.

The heat pump will be modeled by dumping an amount of energy from the solar pool equivalent to that required by the heat pump. The water flow to the heat exchanger will be maintained at the same rate as that required for an actual heat pump to allow a realistic study of the heat transfer mechanisms in the solar pool. The amount of energy dumped will be determined by integrating hourly data. The air flow to the heat exchanger will be adjusted semi-weekly to maintain the average monthly energy required for the heat pump.

H. Activities to Disseminate Project Results

Papers have been presented to the Conference on Solar Energy in Cold Climates (University of Detroit, June 7-8, 1976) and to the conference "Solar Three: Capturing the Sun" (Northwestern University in Evanston, Illinois on November 20, 1976).

In addition, a paper, "Heat Transfer Analysis of a System for Annual Collection and Storage of Solar Energy," was presented to the 1977 ASME Winter Annual Meeting in Atlanta, Georgia, and was published in Heat Transfer in Solar Energy Systems, ASME Publication No. H00104.

Papers have been accepted also for presentation and publication in the proceedings of the International Solar Energy Society Congress 1977 in New Delhi, India (January 16-21, 1978) and of the Southeastern Seminar on Thermal Sciences, 14th Annual Meeting, North Carolina State University, Raleigh, April 6-7, 1978.

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